TITLE: Technologies for Future Precision Strike Missile Systems - Missile Aeromechanics Technology

Technologies for Future Precision Strike Missile Systems - Missile Aeromechanics Technology

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Abstract/Executive Summary

This paper provides an assessment of the state-of-the-art of new aeromechanics technologies for future precision strike missile systems. The aeromechanics technologies are grouped into specific discussion areas of aerodynamics, propulsion, and airframe materials technologies. Technologies that are addressed in this paper are:

- **Missile aerodynamics technologies**. Assessments include aerodynamic configuration shaping, lattice tail control, split canard control, forward swept surfaces, bank-to-turn maneuvering, and flight trajectory shaping.
- **Missile propulsion technologies**. Assessments include supersonic air breathing propulsion, high temperature combustors, low drag ramjet inlets, ramjet inlet/airframe integration, high density fuels, and rocket motor thrust magnitude control.
- **Missile airframe materials technologies**. Assessments include hypersonic structure materials, composite structure materials, hypersonic insulation materials, multi-spectral domes, and reduced parts count structure.

Introduction

Missile aeromechanics technologies have benefits that include enhanced flight performance, reduced weight, increased Mach number, reduced cost, higher reliability, and reduced observables. Figure 1 summarizes new aeromechanics technologies for precision strike missiles. Most of the technologies in the figure are covered in this paper, however there was not sufficient time to address them all. A summary of other new aeromechanics technologies is presented in the Introduction/Overview paper of this lecture series.

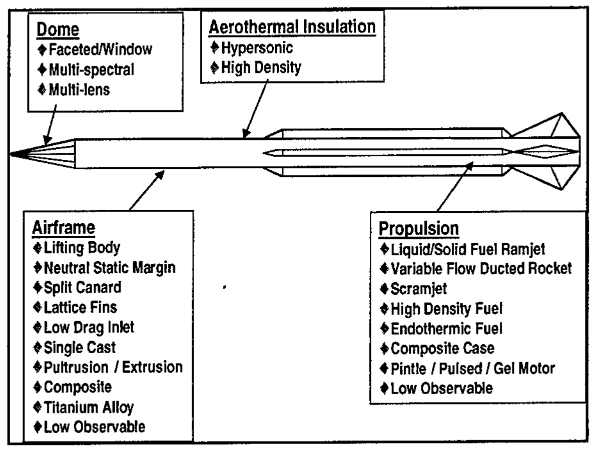


Figure 1. New Aeromechanics Technologies for Precision Strike Missiles.

Missile Aerodynamics Technologies

This assessment of missile aerodynamics technologies addresses six new enabling technologies. These are aerodynamic configuration shaping, lattice tail control, split canard control, forward swept surfaces, bank-to-turn maneuvering, and flight trajectory shaping.

Aerodynamic Configuration Shaping. Figure 2 illustrates aerodynamic configurations that are highly tailored, using aerodynamic shaping of lifting body configurations. An advantage of a tailored lifting body missile is higher aerodynamic efficiency (lift-to-drag ratio) for extended range cruise performance and enhanced maneuverability. Also shown in Figure 2 is the synergy of tailored missiles with reduced radar cross section. Tailored missiles are also synergistic with ramjets for areas such as inlet integration and liquid hydrocarbon fuel packaging. Disadvantages of tailored missiles include relative inefficiency for subsystem packaging and adverse impact on launch platform integration due to a larger span.

Lattice Tail Control. Another example of new aeromechanics technology is lattice tail control. Lattice fins have advantages of lower hinge moment and higher control effectiveness at supersonic Mach number. Figure 3 shows a comparison of lattice tail control with two conventional approaches to tail control - all movable control and flap control. Except for radar cross section, lattice tail control has good-to-superior performance for supersonic missiles. Also shown in the figure are examples of supersonic missiles with tail control alternatives of lattice tail control (Adder AA-12), all movable tail control (ASRAAM AIM-132), and flap tail control (Hellfire AGM-114). The smaller chord length of the lattice has less variation in the center of pressure, resulting in lower hinge moment for lattice tail control.

Paper presented at the RTO SCI Lecture Series on "Technologies for Future Precision Strike Missile Systems", held in Atlanta, USA, 23-24 March 2000; Turin, Italy, 3-4 April 2000; Ankara, Turkey, 6-7 April 2000, and published in RTO-EN-13.

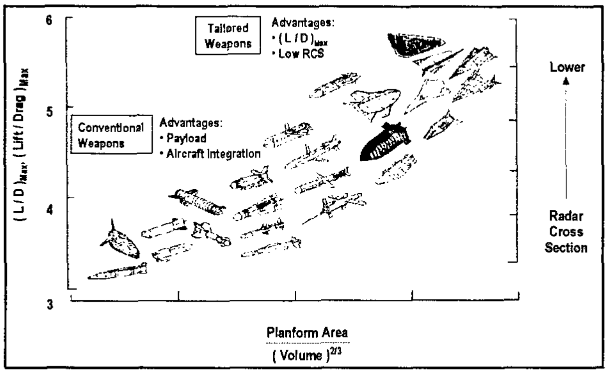


Figure 2. Aerodynamic Shaping Provides Reduced Observables and Higher $(L/D)_{Max}$.

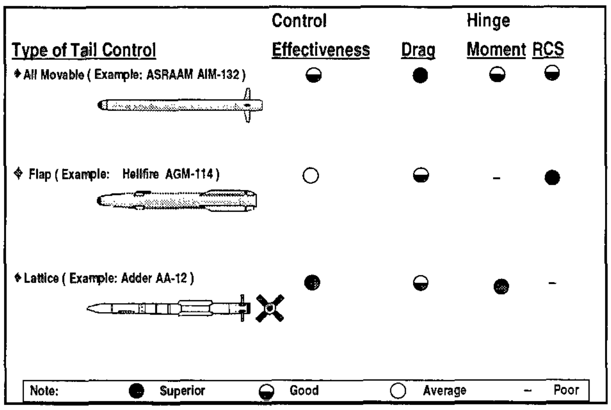


Figure 3. Lattice Tail Control Provides High Control Effectiveness and Low Hinge Moment.

Lattice fins are most appropriate for supersonic missiles. At transonic Mach number, lattice fins have higher drag and lower control effectiveness than traditional flight control. At a low transonic free stream Mach number less than 1, the local flow through the lattice accelerates to Mach 1, choking the flow. For a transonic free stream Mach number slightly greater than 1, the flow through the lattice remains choked. A detached, normal shock wave in front of the lattice spills excess air flow around the lattice. The lattice remains choked until the supersonic Mach number is sufficiently high to allow the lattice to swallow the shock. An oblique shock is then formed on the leading edge of each surface of the lattice. At low supersonic Mach number the oblique shock angle is large. Each oblique shock is reflected downstream, off an adjacent lattice surface, resulting in increased drag. At higher Mach number the oblique shock angle is smaller, passing through the lattice without intersecting a lattice surface. Lattice fins have their best application at high supersonic Mach number, where they have lower drag and higher control effectiveness.

Split Canard Control. Modern highly maneuverable missiles are using split canards for flight control. Split canard control has a flat surface in front of the movable canard. Figure 4 is a schematic of the local flow that illustrates the advantage of split canards. The incremental normal force coefficient, ΔC_N, in the figure is the difference between the normal force coefficient of the deflected control surface and the normal force coefficient of an undeflected control surface. Note that the forward surface reduces the local effective angle of attack (AOA). Because the trailing canard control surface has a smaller local angle of attack, it is more effective at higher control surface deflection, δ, and higher angle of attack, α, operating without stall. All modern canard control missiles use split canard control including Kegler AS-12, Archer AA-11, Aphid AA-8, Magic R-550, and Python 4.

Forward Swept Surfaces. Forward swept surfaces are an alternative to the traditional aft swept surfaces for missile canards, tails, and wings. Forward swept surfaces are particularly beneficial for missiles that have small span requirements for aircraft compatibility. Figure 5 is a comparison of a forward swept leading edge surface with conventional planform surfaces that are triangular (delta), trapezoidal with an aft swept leading edge, and rectangular. In addition to a smaller span requirement, forward swept surfaces have good-to-superior characteristics of low variation in aerodynamic center, low bending moment, low supersonic drag, low radar cross section, and high control effectiveness. An

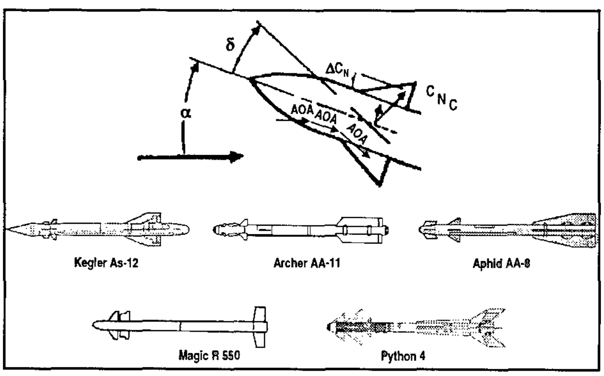


Figure 4. Split Canards Provide Enhanced Maneuverability at High Angles of Attack.

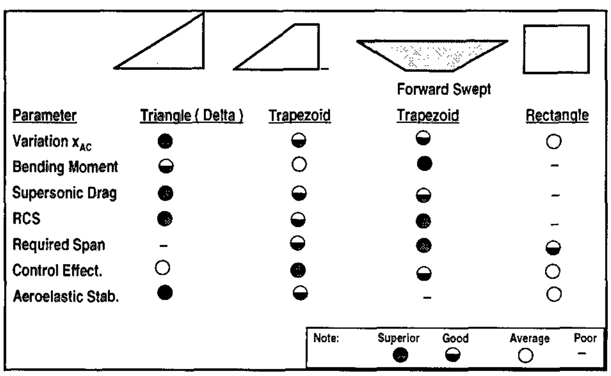


Figure 5. Forward Swept Surfaces Allow Small Span and Have Low Bending Moment.

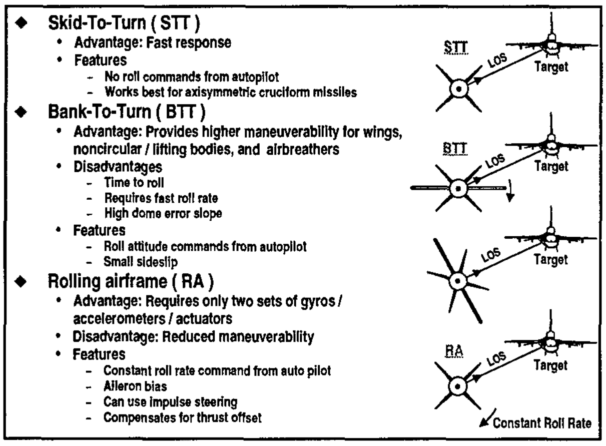


Figure 6. Bank-to-Turn Provides Higher Maneuverability

inherent disadvantage of a forward swept surface is increased potential for aeroelastic instability. Composite structure is synergistic with forward swept surfaces because the higher stiffness of composites mitigates aeroelastic instability.

Bank-to-turn Maneuvering. Figure 6 compares bank-to-turn maneuvers with maneuver alternatives of skid-to-turn and rolling airframe. Missiles using bank-to-turn will first roll until the wings or the major axis of a lifting body are oriented perpendicular to the target line-of-sight. Following the roll maneuver, the missile then maneuvers in pitch, maintaining the preferred roll orientation. A benefit of bank-to-turn maneuvering is higher maneuverability for a lifting body with noncircular cross section or for a missile with wings. Another benefit is smaller sideslip angle for missiles with inlets. Bank-to-turn is particularly suited for mid-course guidance maneuvers. A disadvantage of bank-to-turn maneuvering is slower response in terminal maneuvers that could degrade guidance accuracy, increasing the missile miss distance. Alternative approaches to alleviate this problem include faster actuators for roll control, faceted or multi-lens dome, and switching from bank-to-turn maneuvering to skid-to-turn maneuvering for terminal flight.

Flight Trajectory Shaping. Figure 7 illustrates the extended range advantage of precision strike missiles that use flight trajectory shaping. Flight trajectory shaping is particularly beneficial for high performance supersonic missiles, which have large propellant or fuel weight fraction. To take advantage of flight trajectory shaping, the missile must rapidly pitch up and climb to an efficient cruise altitude. During the climb, the missile angle-of-attack should be small, to minimize drag. Missile thrust-to-weight ratio should also be relatively low (~2). Thrust-to-weight ratios greater than about two result in high dynamic pressure, increasing drag. After reaching higher altitude, the missile benefits from cruising at improved lift-to-drag ratio, or aerodynamic efficiency. Dynamic pressure

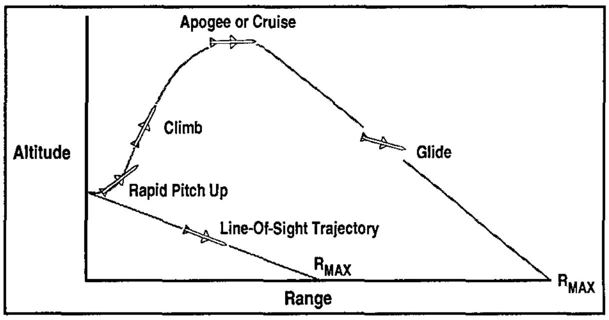


Figure 7. Flight Trajectory Shaping Provides Extended Range.

for efficient cruise of a high performance supersonic missile is of the order of 500 to 1,000 pounds per square foot. Following burnout, the missile can also have extended range through glide at a dynamic pressure of about 700 pounds per square foot.

Missile Propulsion Technologies

The assessment of missile propulsion technologies addresses six new enabling technologies. These are supersonic air breathing propulsion, high temperature combustors, low drag ramjet inlets, ramjet inlet/airframe integration, higher density fuels, and rocket motor thrust magnitude control.

Supersonic Air Breathing Propulsion. Ramjets, scramjets, and ducted rockets have high payoff for precision strike missiles operating at supersonic/hypersonic Mach number. A comparison of the specific impulse performance of ramjet, scramjet, and ducted rocket propulsion, along with that of solid rocket and turbojet propulsion, is given in Figure 8.

Turbojet and turbofan propulsion is a relatively mature technology for precision strike missiles. Turbojets/turbofans are most suited for subsonic cruise missiles, providing high efficiency to deliver a warhead at long range against non-time-critical targets. The operating regime is from Mach 0 to about Mach 3. However, beyond Mach 2, increasingly complex inlet systems are required to match delivered inlet airflow to compressor capacity, and expensive cooling systems are required to avoid exceeding material capabilities at the turbine inlet.

Solid rockets are capable of providing thrust across the entire Mach number range. Although the specific impulse of tactical rockets is relatively low, of the order of 250 seconds, rockets have an advantage of much higher acceleration capability than air-breathing propulsion. Solid rocket boosters are used to boost ramjets to their take-over Mach number of about 2.5, for transition to air-breathing propulsion.

The maximum specific impulse of a liquid hydrocarbon fuel ramjet is about 1500 seconds, much

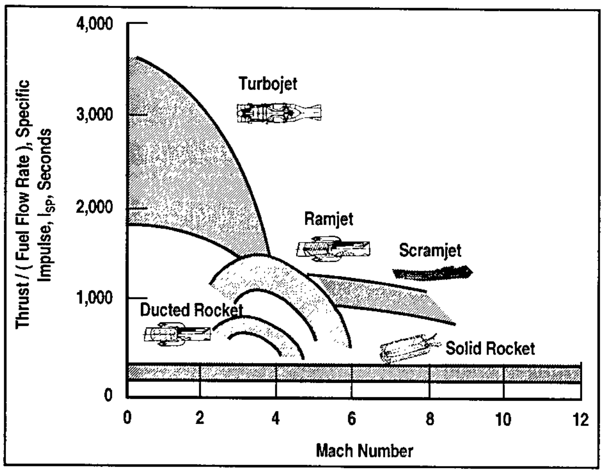


Figure 8. Ramjets and Scramjets Have High Payoff at Supersonic/Hypersonic Mach Number.

higher than the specific impulse of a solid rocket. An efficient cruise condition for a ramjet is about Mach 4, 80K feet altitude. Above Mach 5, deceleration of the inlet airflow to subsonic velocity results in chemical dissociation of the air, which absorbs heat and reduces the useful energy output of the combustor. Ramjets are synergistic with noncircular, lifting body airframes because ramjet fuel can be stored in noncircular tanks. Liquid fuel ramjets can be throttled, for efficient matching of the fuel with the inlet airflow. Throttling provides higher thrust and specific impulse over a broader flight envelope of Mach number and altitude. A high throttle setting also allows supersonic impact and deep penetration of buried targets.

Above Mach 6, a supersonic combustion ramjet (scramjet) provides higher performance than a ramjet. The minimum sustained flight Mach number of a scramjet, based on providing sufficient thrust to overcome missile drag, is greater than about Mach 4.0. The maximum Mach number, based on engine material temperature limit, is about Mach 8 to 9. An efficient cruise condition for a scramjet is about Mach 6, 100K feet altitude. A key technical challenge is fuel mixing for efficient supersonic combustion. There are extremely short residence times for supersonic combustion. An enabling technology to enhance supersonic combustion is endothermic fuels. Endothermic fuels decompose at high temperature into lighter weight molecular products that burn more readily, providing higher specific impulse and permitting shorter combustor length. An endothermic fuel also acts as a heat sink, cooling the adjacent structure. Like the ramjet, the scramjet is rocket boosted to a supersonic takeover speed. Takeover speed of a scramjet is higher than a ramjet, about Mach 4.5, requiring a larger booster. For a weight-limited system, a hypersonic scramjet missile will have less available fuel than a supersonic ramjet missile.

Referring again to Figure 8, note that the maximum specific impulse of ducted rocket propulsion is about

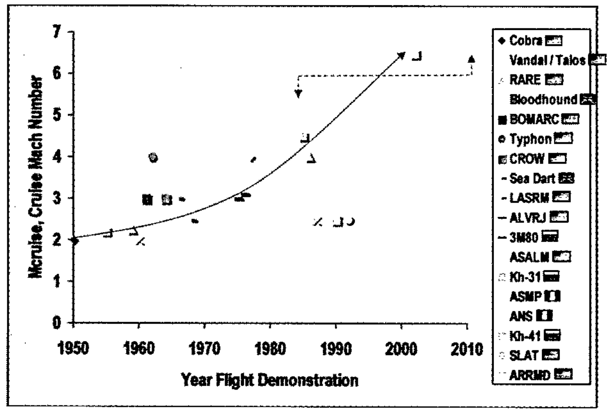


Figure 9. State-of-the-Art Evolution in Supersonic/Hypersonic Air Breathing Missiles.

800 seconds, intermediate that of a solid rocket and a ramjet. Ducted rockets are most efficient for a Mach number range from about 2.5-4.0. Ducted rockets have advantages of higher acceleration capability (higher thrust) than ramjets and longer range capability (higher specific impulse) than solid rockets. A ducted rocket is particularly suited for the suppression of long range, high performance SAMs. The acceleration and fast response to Mach 3+ provides a short response time for an anti-SAM engagement. Ducted rockets utilize a gas generator to provide fuel-rich products to the combustor. The gas generator flow rate can be controlled, providing a throttle capability for thrust magnitude control. Air from the inlet mixes with the fuel-rich products from the gas generator, providing additional burning. The relatively high acceleration capability of the ducted rocket is due to the momentum of the gases from the gas generator. A disadvantage of the ducted rocket is lower specific impulse than a ramjet. Because the gas generator includes an oxidizer, the total energy stored in the gas generator is less than that of a ramjet or scramjet fuel tank of the same volume. In addition to a relatively high thrust capability of a ducted rocket compared to a ramjet or scramjet, a solid ducted rocket has advantages of lower maintenance requirements and better shipboard compatibility than a liquid fuel ramjet or scramjet.

Figure 9 shows a history of the state-of-the-art advancement for supersonic/hypersonic air breathing missiles over the last fifty years. A number of ramjet demonstrations have been conducted over the years. As shown in the figure, the cruise Mach number demonstrations have provided higher confidence in the capability for efficient hypersonic cruise. Ramjets have demonstrated supersonic and hypersonic cruise up to Mach 4.5. A future flight demonstration of a scramjet plans to demonstrate Mach 6.5 cruise in the year 2002 time frame.

High Temperature Combustors. Higher combustion temperature has payoff in improving the specific impulse and thrust of ramjet missiles, enabling flight at higher Mach number. Figure 10 shows the ideal

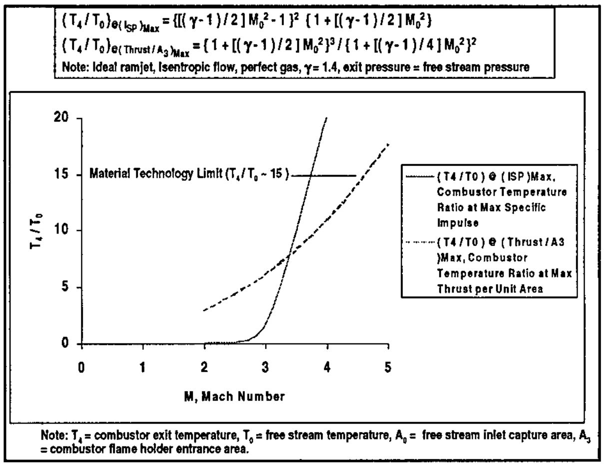


Figure 10. High Combustor Temperature Has High Payoff at Hypersonic Mach Number.

combustion temperature for maximum specific impulse and thrust of an ideal ramjet as a function of Mach number. Results are based on an assumption of isentropic flow, perfect gas, and nozzle expansion to atmospheric pressure. The state-of-the-art for current combustor material technology is about 5,000 degrees Rankine. At a combustor temperature of 5,000 degrees Rankine, the ratio of combustor temperature to freestream temperature is approximately 15. As shown in the figure, for a combustor temperature ratio of 15, maximum specific impulse for a ramjet is produced at a Mach number of about 3.5. Also shown is the Mach number for maximum thrust per unit frontal area. The maximum thrust per unit frontal area is produced at a Mach number of about 4.7. Future improvement in the technology for maximum allowable temperature of combustor materials will allow ramjets to operate more efficiently at higher Mach number.

Low Drag Ramjet Inlets. Examples of low drag inlet alternatives for ramjets are shown in Figure 11. Current operational ramjets have either a nose inlet (United Kingdom Sea Dart) or aft axisymmetric inlets (France ANS and ASMP, Russia AS-17/Kh-31, Kh-41, and SS-N-22/3M80). A nose inlet has lower drag, while aft axisymmetric inlets are lighter weight, have lower volume, and do not degrade warhead effectiveness.

Ramjet Inlet/Airframe Integration. Because ramjet combustion is subsonic, there must be a normal shock in the inlet to provide subsonic flow into the combustor. Small oblique shocks prior to the normal shock alleviate the problem of total (stagnation) pressure loss across the normal shock. Figure 12 compares a single, normal shock total pressure recovery with that of one, two, and three oblique shocks prior to the normal shock. An example is shown of a chin inlet ramjet that has two oblique shocks (from a conical forebody angle of 17.7 degrees and an inlet ramp angle of 8.36 degrees). As shown in the example, the stagnation pressure recovery ratio at

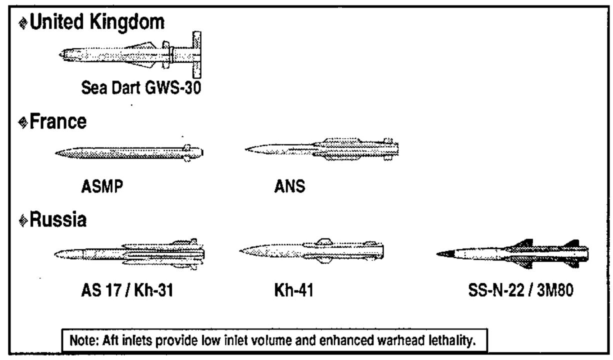
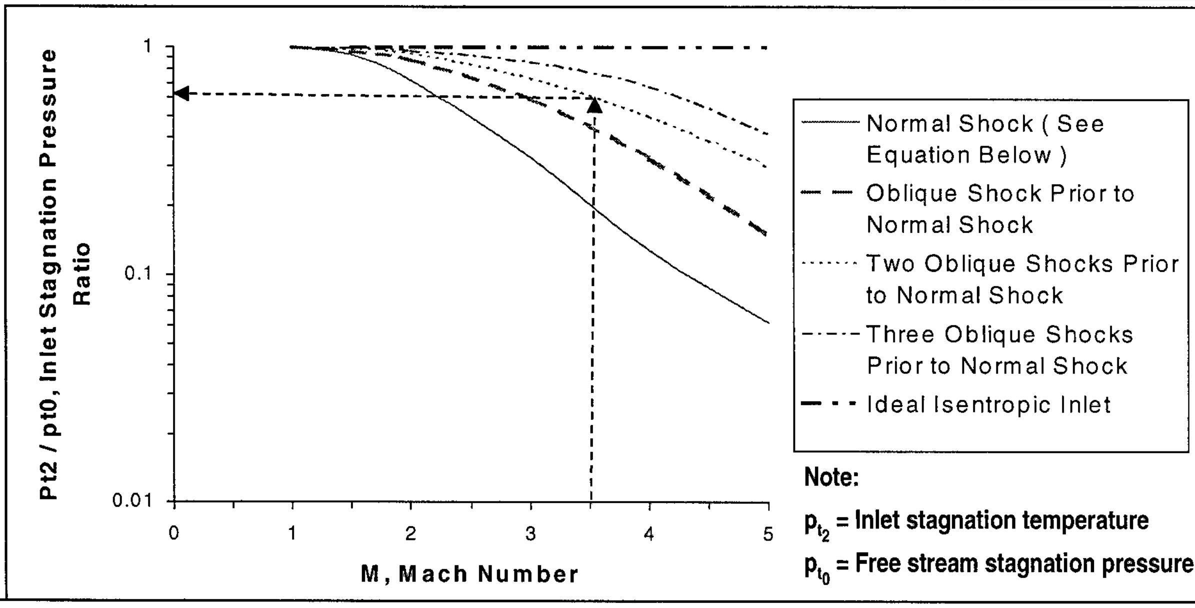


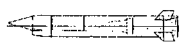
Figure 11. Current Ramjet Inlets Are Either Low Drag Nose or Low Drag Aft Axisymmetric.

Mach 3.5 is 62% if there are two oblique shocks. This stagnation pressure recovery is much higher than that for the case of one oblique shock prior to the normal shock or for the case of a single normal shock. Ramjet inlet/airframe integration through forebody compression (such as a chin inlet) and an optimized inlet cowl lip angle provides higher specific impulse and higher thrust.

High Density Fuels. Another area of new propulsion advancement is that of higher density fuel. Higher density fuels provide high volumetric performance for volume limited missiles (Figure 13). Current fuels for turbines such as JP-5, JP-7, and JP-10 have relatively low density, of the order of 0.028 pounds per cubic inch, and low volumetric performance, of the order of 559 BTUs per cubic inch. Liquid fuel ramjet hydrocarbon fuels such as RJ-4, RJ-5, RJ-6, and RJ-7 have somewhat higher density and higher volumetric performance. Slurry fuels, such as JP-10 with carbon slurry, and solid hydrocarbon fuels have much higher volumetric performance, at the expense of somewhat higher visual observables. Even better performance is achievable with high density, solid metal fuels such as magnesium, aluminum, and boron. For example, solid boron fuel provides over 3X the volumetric performance of liquid hydrocarbon fuels. However, metal fuels have high visual observables from their plumes.

Rocket Motor Thrust Magnitude Control. An approach to energy management for a solid rocket is thrust magnitude control. Alternatives include pulsed and pintle motors (Figure 14). The solid pulsed motor uses thermal or mechanical barriers to separate two or more pulses. The time delay between pulses can be controlled to optimize the flight trajectory profile. As a result, a boost-coast-boost-coast pulsed motor can have longer range and reduced aerodynamic heating compared to a conventional boost-coast motor. The second approach to thrust magnitude control, a solid pintle motor, has a pintle plug that is moved in and out of the throat area. Moving the pintle into the throat area provides increased chamber pressure and higher thrust, while moving the pintle out of the throat area decreases the chamber pressure and thrust. Pintle



Example for Ramjet Baseline: 

Two oblique shocks (conical forebody angle = 17.7 deg, inlet ramp angle = 8.36 deg)

Mach 3.5, $p_{t_2} / p_{t_0} = 0.62$, $I_{SP} = 0.62 (1616) = 1002$ sec. Note: $I_{SP} = 1616$ sec for a perfect inlet.

Note: For Normal Shock Inlet, $p_{t_2} / p_{t_0} = \{\{[(\gamma + 1) M_0^2] / [2 + (\gamma - 1) M_0^2]\}^{\gamma / (\gamma - 1)}\} / \{ 1 + [2 \gamma / (\gamma + 1)] [(M_0^2 - 1)]\}^{1 / (\gamma - 1)}$

Source: Oswatitsch, K., "Pressure Recovery for Missiles with Reaction Propulsion at High Supersonic Speeds", NACA TM - 1140, 1948.

Figure 12. Ramjet Inlet/Airframe Integration Has Payoff.

Type	Volumetric Performance, BTU / in^3		Low Observables
Turbine (JP-5, JP-7, JP-10), $\rho \sim 0.028$ lb / in^3	○	559	●
Liquid Ramjet (RJ-4, RJ-5, RJ-6, RJ-7), $\rho \sim 0.040$ lb / in^3	○	581	●
Slurry (40% JP-10 / 60% carbon), $\rho \sim 0.049$ lb / in^3	◒	801	○
Solid Hydrocarbon, $\rho \sim 0.075$ lb / in^3	●	1132	○
Slurry (40% JP-10 / 60% aluminum), $\rho \sim 0.072$ lb / in^3	◒	866	–
Slurry (40% JP-10 / 60% boron carbide), $\rho \sim 0.050$ lb / in^3	●	1191	–
Solid Mg, $\rho \sim 0.068$ lb / in^3	●	1300	–
Solid Al, $\rho \sim 0.10$ lb / in^3	●	1300	–
Solid Boron, $\rho \sim 0.082$ lb / in^3	●	2040	–

● Superior ◒ Above average ○ Average – Below average

Figure 13. High Density Fuels Provide Higher Volumetric Performance.

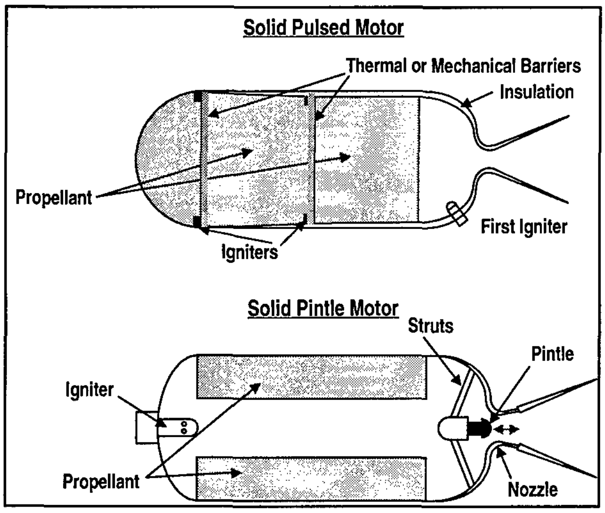


Figure 14. Thrust Magnitude Control Provides Efficient Thrust Management.

motors have demonstrated maximum-to-minimum thrust ratios of up to six-to-one. However, larger thrust ratio is at the expense of reduced specific impulse. A third potential alternative for thrust magnitude control is a gel propellant motor. Gel propellants have not yet been accepted for tactical missile applications, particularly for naval platforms, due to concerns of toxicity.

Missile Airframe Materials Technologies

The assessment of missile airframe materials technologies addresses five new enabling technologies. These are hypersonic structure materials, composite structure materials, hypersonic insulation materials, multi-spectral domes, and reduced parts count structure.

Hypersonic Structure Materials. Examples of structure materials that are cost effective for precision strike missiles are shown in Figure 15. The materials are based on consideration of weight, cost, and maximum temperature capability. Composite materials are a new technology that will find increased use in new missile airframe structure. High temperature composites have particular benefits for hypersonic missiles, providing weight reduction. Titanium alloy technology also enables lighter weight missiles in a hypersonic, high temperature flight environment.

As shown in the figure, at subsonic and low supersonic Mach number, graphite epoxy and aluminum or aluminum alloys are attractive choices for light weight structure. Graphite epoxy and aluminum alloys have high strength-to-weight ratio, are easily fabricated, have good corrosion resistance, and are low in cost. For higher Mach number,

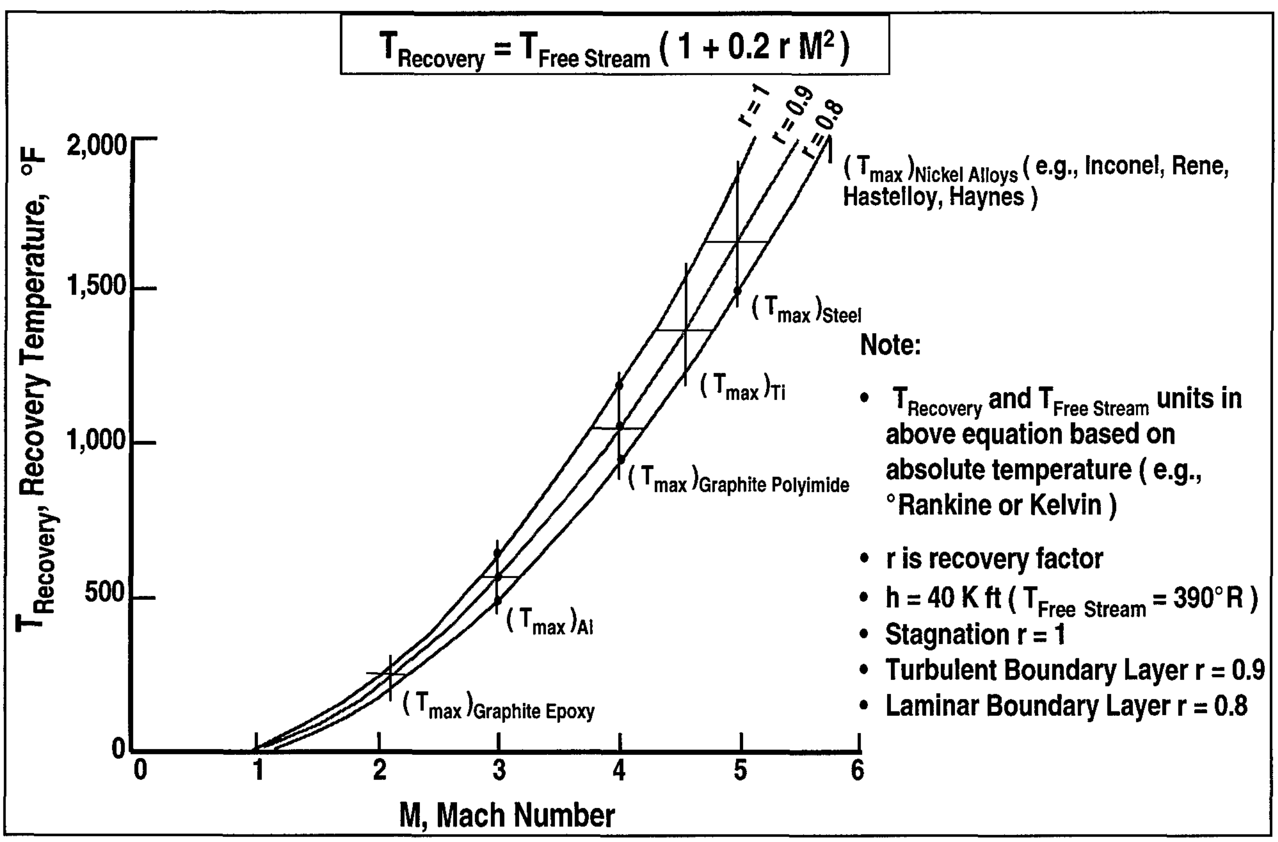


Figure 15. Hypersonic Missiles Require High Temperature Structure.

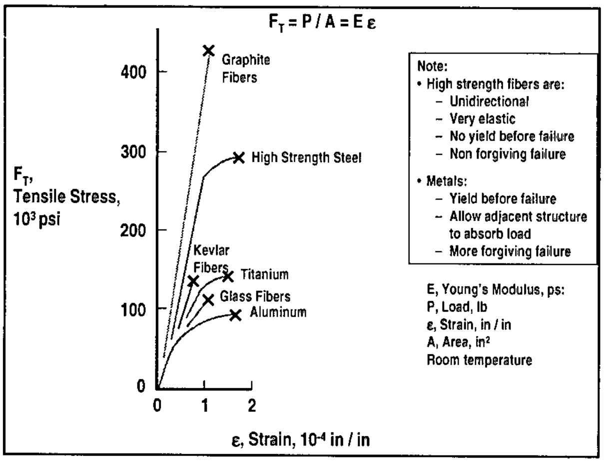


Figure 16. Composites Have High Strength.

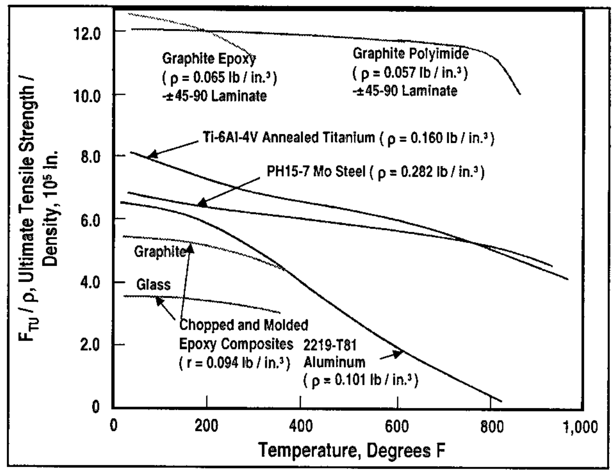


Figure 17. Composites Have High Structural Efficiency.

graphite polyimide composite structure has the advantage of high structure efficiency at higher temperature for Mach numbers to about Mach 4. For flight at about Mach 4.5, titanium structure and its alloys becomes the best candidate. At Mach 5, although it is heavy, a steel structure would probably be used. Above about Mach 5.7, (about 2,000 degrees Fahrenheit), super nickel alloys such as Inconel, Rene, Hastelloy, and Haynes must be used. The Mach number and temperature application relationships are somewhat dependent upon the temperature recovery factor. At a stagnation region, such as the nose or leading edges, the recovery factor is about 1, resulting in the highest (stagnation) temperature. A turbulent or laminar boundary layer downstream of the nose or leading edge will have temperature recovery factors of about 0.9 and 0.8 respectively, with local temperatures less than stagnation.

Composite Structure Materials. The strength-to-weight capability of advanced composites is very high. For example, as shown in Figure 16, the unidirectional tensile strength of graphite (carbon) fiber is more than 400K pounds per square inch. Advanced composite structures have continuous fibers, greater than 50% fibers by volume. Fibers can be graphite (carbon), kevlar, boron, ceramic, silicon carbide, quartz, polyethylene, and others. As an example of strength at the structure level, 50% volume graphite composite structure would have a strength of the laminate above 200K pounds per square inch, much greater than that of aluminum, or even steel. Also the low density of composites further reduces the weight compared to metals. Graphite fiber composite materials have extremely high modulus of elasticity, resulting in low strain and deflection compared to metals. However, a note of caution, unlike metals that generally yield gracefully before ultimate failure, composite fibers fail suddenly without yield.

Figure 17 shows the structural efficiency advantage of composites compared to conventional materials. For temperatures up to about 300 degrees Fahrenheit, graphite epoxy is a good candidate material, based on its characteristics of high strength and low density. Graphite polyimide can be used at even higher temperatures, up to about 900 degrees Fahrenheit. Above 900 degrees Fahrenheit, titanium and steel are the best materials based on strength-to-weight ratio.

Hypersonic Insulation Materials. An area of enabling capability for hypersonic precision strike missiles is short duration insulation technology. Because hypersonic precision strike missiles have stringent volume and weight constraints, higher density external airframe and internal insulation materials are in development. Higher density insulation materials permit more fuel/propellant, resulting in longer range. Thermal insulators are used to provide short duration protection of structural materials from either the aerodynamic heating of a hypersonic free stream or from propulsion heating of the combustion chamber and exhaust gases of the nozzle. Figure 18 shows the maximum temperature and short duration insulation efficiency of candidate insulation materials.

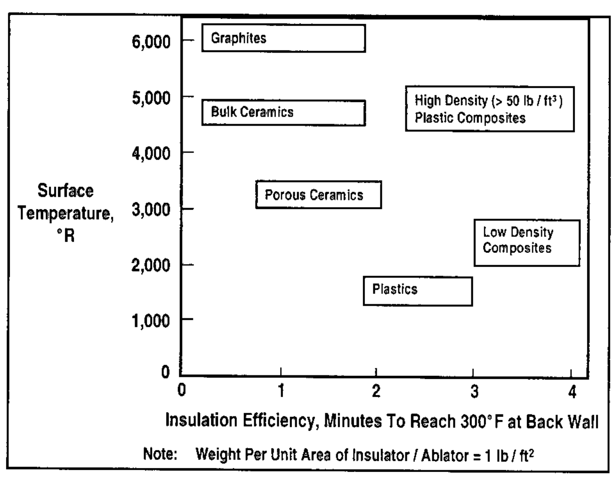


Figure 18. Composites Provide Light Weight Insulation.

Note that composite materials are good candidates for light weight insulation. For high-speed precision strike missiles, relatively high density plastic composites, such as fiberglass reinforced phenolic resins containing nylon, silica, graphite, or carbon are often used. These have good resistance to erosion, allow high surface temperatures up to 5,000 degrees Rankine, and exhibit good insulation performance. High density plastic composite materials char at high temperature, but maintain their thickness and aerodynamic shape. They are usually fabricated by wrapping fiberglass tape over a metal form mandrel, so that the grain of the finished unit is oriented for minimum erosion. Cross flow orientation, or other grain directional orientation, is optimized to minimize the amount of the material that is required. After winding, the tape is cured, machined as necessary, and assembled with other components using adhesives and sealants. Another example of a good insulator at somewhat lower temperatures is low density composites. Low density composites such as glass cork epoxy or silicone rubber may be used for temperatures up to about 2800 degrees Rankine. A disadvantage of low density composites is that at high temperatures they decompose into gases and sublime, resulting in decreased thickness and changes in the aerodynamic shape. Low density composites are also relatively soft, requiring periodic maintenance touch-up.

Ceramic refractory materials and graphite materials are also candidate insulators for hypersonic missiles. Although ceramic refractory materials and graphites have high temperature capability, the insulation efficiency for a given weight of material is not as good as that of high density plastic composite materials. An example of a porous ceramic, with a maximum temperature up to about 3,500 degrees Rankine, is resin impregnated carbon-silicon carbide. At high temperatures the resin melts, providing cooling for the structure. Examples of bulk ceramics are zirconium ceramic and hafnium ceramic. Bulk ceramics are capable of withstanding temperatures up to 5,000 degrees Rankine, but like porous ceramics, they have relatively poor insulation efficiency. Finally, graphite insulators provide the highest temperature capability. Graphites are capable of withstanding temperatures greater than 5,000 degrees Rankine. Graphites are also known as carbon-carbon, fibrous graphite, prepyrolyzed composites, graphite-graphite composites, and graphite composites. Graphites are usually formed by pressure molding at a temperature high enough so that all the material has charred and converted to carbon or graphite. Graphites contain a graphite or carbon fabric, fiber, filament, or felt reinforcement bonded together, with carbon or graphite as the bonding material.

Airframe structure/insulation trades include hot structure/internal insulation versus external insulation/"cold" structure versus a one-piece self-insulating composite structure. A consideration for a volume-limited missile is the total thickness of the airframe/insulation. Large thickness means less volume for fuel, resulting in less range.

Multi-spectral Domes. Multi-spectral domes are broad bandpass domes that are compatible with multi-spectral (e.g., mid-wave IR/long wave IR) and multi-mode (e.g., IR/millimeter wave) seekers. Figure 19

Seeker Dome Material	Density (gm / cm³)	Dielectric Constant	MWIR / LWIR Bandpass	Transverse Strength (psi)	Thermal Expansion (10^{-6} / °F)	Erosion, Knoop (kg / mm²)	Max Short-Duration Temp (°F)
RF / IR							
Zinc Sulfide (Z_nS)	4.05	○ 8.4	●	○ 18	○ 4	○ 350	○ 700
Zinc Selenide (Z_nS_e)	5.16	◡ 9.0	●	◡ 8	○ 4	○ 150	○ 600
Spinel ($M_gAl_2O_4$)	3.68	○ 8.5	●	○ 28	○ 3	● 1650	● 1800
Quartz / Fused Silicon (S_iO_2)	2.20	● 3.7	○	◡ 8	● 0.3	◒ 600	● 2000
Silicon Nitride (Si_3N_4)	3.18	◒ 6.1	◒	● 90	◒ 2	● 2200	● 2700
Diamond (C)	3.52	◒ 5.6	◡	● 400	● 1	● 8800	● 3500
RF Only							
Pyroceram	2.55	◒ 5.8	◡	○ 25	○ 3	◒ 700	● 2200
Polyimide	1.54	● 3.2	◡	○ 17	◡ 40	◡ 70	◡ 200
MWIR Only							
Mag. Fluoride (M_gF_2)	3.18	◒ 5.5	●	◡ 7	◡ 6	◒ 420	◒ 1000
Alon ($Al_{23}O_{27}N_5$)	3.67	◡ 9.3	●	◒ 44	○ 3	● 1900	● 1800

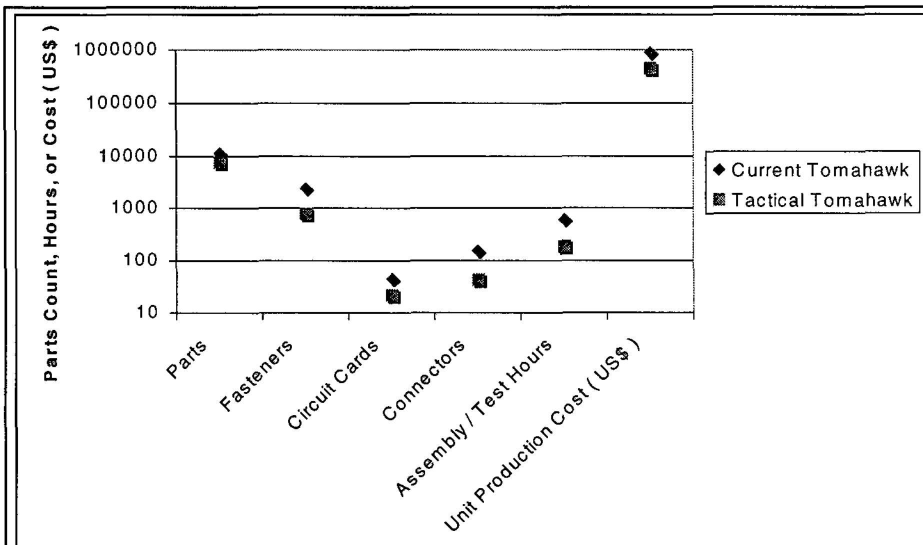
● Superior ◒ Above Average ○ Average ◡ Below Average

Figure 19. Broad Bandpass Domes Support Multi-Mode/Multi-Spectral Seekers.

compares measures of merit for combined radar/infrared dome materials with radar-only and infrared-only dome materials. Measures of merit are dielectric constant, combined mid-wave/long wave infrared bandpass, transverse strength, thermal expansion, erosion resistance, and maximum short duration temperature. Current dome materials that can be used for combined radar and infrared seekers include zinc sulfide and zinc selenide. Zinc sulfide has advantages in dielectric constant and transverse strength, while zinc selenide has an advantage of less rain erosion. Zinc sulfide is generally the multi-mode dome material of choice for Mach numbers up to 3. For Mach number greater than 3, new materials will be required for multi-mode seekers. Candidate materials include spinel, quartz/fused silicon, and silicon nitride. These materials are more expensive than zinc sulfide and zinc selenide. A new candidate dome material that is under development for missile defense applications is diamond. Obviously cost is very high for a diamond dome. In addition to high material cost, diamond dome assembly cost is high. Diamond domes must be assembled as a built-up mosaic because the individual diamonds are relatively small size.

Reduced Parts Count Structure. Airframe cost and producibility are important considerations for precision strike missiles. New airframe technology is in development that will reduce the cost of precision strike weapons. Examples of recent precision strike weapons that include low cost technologies include JDAM and JASSM. Technologies to reduce cost are also being introduced into existing weapons, with large savings. An example is Tactical Tomahawk. It has a simple low cost airframe with extruded wings that enables the introduction of low cost commercial parts for G&C and propulsion. The current Tomahawk has 11,500 parts, 2,500 fasteners, 45 circuit cards, 160 connectors, and requires 610 assembly/test hours. Tactical Tomahawk will have 35% fewer parts, 68% fewer fasteners, 51% fewer circuit cards, 72% fewer connectors, and 68% fewer assembly/test hours – resulting in a 50% reduction in cost (Figure 20). Tactical Tomahawk also has superior flexibility (e.g., shorter mission planning time, capability for in-flight targeting, capability for battle damage indication/battle damage assessment, modular payload) and higher reliability at the same launch weight as the current Tomahawk.

Precision castings will also become more prevalent in precision strike missiles. Castings reduce the parts count, with a resulting cost savings. Large precision cast structures are in development for complex missile shapes, such as ramjets. A one-piece cast airframe design integrates all of the secondary structure to minimize parts count. Precision tooling minimizes subsequent machine and hand finishing of mating surfaces, by achieving a precision surface finish "as-cast." Fuel cells can be an integral part of the structure and not require bladders. Structural attachment points (e.g., ejector attachments, payload supports, booster attachments.) and self-indexing/aligning features can be integral to the structure. This minimizes or eliminates mating/alignment/assembly tooling and test (inspection) requirements. Precision castings have been demonstrated for missile aluminum, titanium, and steel airframes, motor cases, and combustors. Ceramic tooling is an enabling technology for low cost precision castings.



Note: Tactical Tomahawk has superior flexibility (e.g., shorter mission planning, in-flight retargeting, BDI / BDA, modular payload) at lower parts count / cost and higher reliability. Enabling technologies for low parts count include: casting, pultrusion / extrusion, centralized electronics, and COTS.

Figure 20. Low Parts Count Reduces Missile Cost.